Risk for ACPA-positive rheumatoid arthritis is driven by shared HLA amino acid polymorphisms in Asian and European populations

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Previous studies have emphasized ethnically heterogeneous human leukocyte antigen (HLA) classical allele associations to rheumatoid arthritis (RA) risk. We fine-mapped RA risk alleles within the major histocompatibility complex (MHC) in 2782 seropositive RA cases and 4315 controls of Asian descent. We applied imputation to determine genotypes for eight class I and II HLA genes to Asian populations for the first time using a newly constructed pan-Asian reference panel. First, we empirically measured high imputation accuracy in Asian samples. Then we observed the most significant association in HLA-DRβ1 at amino acid position 13, located outside the classical shared epitope ($P_{omnibus} = 6.9 \times 10^{-135}$). The individual residues at position 13 have relative effects that are consistent with published effects in European populations (His > Phe > Arg > Tyr ≅ Gly > Ser)—but the observed effects in Asians are generally smaller. Applying stepwise conditional analysis, we identified additional independent associations at positions 57 (conditional $P_{omnibus} = 2.2 \times 10^{-33}$) and 74 (conditional $P_{omnibus} = 1.1 \times 10^{-8}$). Outside of HLA-DRβ1, we observed independent effects for amino acid polymorphisms within HLA-B (Asp9, conditional $P = 3.8 \times 10^{-6}$) and HLA-DPβ1 (Phe9, conditional $P = 3.0 \times 10^{-5}$) concordant with European populations. Our trans-ethnic HLA fine-mapping study reveals that (i) a common set of amino

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acid residues confer shared effects in European and Asian populations and (ii) these same effects can explain ethnically heterogeneous classical allelic associations (e.g. *HLA-DRB1* *09:01*) due to allele frequency differences between populations. Our study illustrates the value of high-resolution imputation for fine-mapping causal variants in the MHC.

INTRODUCTION

Rheumatoid arthritis (RA) is a chronic autoimmune disease characterized by a symmetric polyarticular inflammatory arthritis, which affects up to 1% of the population worldwide (1). The majority of affected RA cases (∼70%) are seropositive for anti-citrullinated protein antibodies (ACPA), a highly specific biomarker of RA related to disease severity (2). The major histocompatibility complex (MHC) region at chromosome 6p21.3 contributes substantially to the heritability of ACPA-positive RA (3–5). Indeed, many reports have implicated consensus amino acid sequences spanning positions 70–74 in the human leukocyte antigen (HLA)-DRβ1 subunit (6) for conferring RA risk, suggesting a critical role for these so-called 'shared epitope' (SE) alleles in the etiology of RA (4,5,7–9). Previous studies assessing the role of the MHC in modulating RA risk demonstrated both shared and distinct features between Asians and Europeans. Even though classical SE alleles of *HLA-DRB1* have been reported to confer strong risks in both continental populations (5–7), heterogeneity of effect sizes (7) and the population-specific associations of non-SE alleles in *HLA-DRB1* (e.g. *HLA-DRB1*09:01* risk in the Asian populations) (10,11) has made it challenging to draw definitive conclusions about the role of *HLA-DRB1* in RA susceptibility.

Recently, we fine-mapped RA risk in European populations within the MHC region to three amino acid positions in HLA-DRβ1 (at positions 11 or 13, 71 and 74) and single amino acid positions in HLA-B (at position 9) and HLA-DPβ1 (at position 9) (12). All these amino acid polymorphisms are located in peptide-binding grooves of HLA molecules, suggesting a critical role for antigen binding and presentation. It is not yet known specifically whether the same alleles at position 13 or at other sites explain RA risk in non-European populations. Here, we explored in detail the possibility that our HLA amino acid variant risk model established in European populations might also explain RA risk in Asian populations.

To this end, we analyzed genetic variation in 2782 ACPA-positive RA cases and 4315 controls from China and South Korea, with each subject densely genotyped across the MHC. In order to apply imputation methods, we newly created a high-density reference panel including genotyped classical four-digit alleles of eight class I and II HLA genes in Asians. With this reference panel, we imputed sequence variation in classical HLA genes, fine-mapped the MHC association for RA risk, and compared results with previous fine-mapping findings in European populations.

RESULTS

Construction and evaluation of a pan-Asian reference panel for imputation of HLA variants

We constructed a pan-Asian reference panel with high-density SNP genotypes and four-digit classical HLA allele genotypes

(*n* = 530; Supplementary Material, Table S1). The newly constructed Asian reference panel consists of three datasets: (i) the Singapore Chinese population (*n* = 91) (13); (ii) pan-Asian datasets including 111 Chinese, 119 Indian and 120 Malaysian subjects (*n* = 350) (13) and (iii) HapMap Phase II Japanese and Han Chinese (JPT + CHB) populations (*n* = 89) (14). Four-digit classical typing data for class I HLA genes (*HLA-A*, *HLA-B* and *HLA-C*) and class II genes (*HLA-DRB1*, *HLA-DQA1* and *HLA-DQB1*) were available for all three datasets. We had access to four-digit classical typing data for *HLA-DPA1* and *HLA-DPB1* for datasets (i) and (ii), but not for (iii).

To evaluate the imputation accuracy of this pan-Asian reference panel, we excluded the HapMap JPT + CHB samples from the panel to avoid sample overlap, and subsequently compared imputed and genotyped classical alleles of the six HLA genes (*HLA-A*, *B*, *C*, *DRB1*, *DQA1* and *DQB1*) in these 89 subjects (Table 1). The imputations based on this pan-Asian reference panel (*n* = 441; not including the HapMap JPT + CHB subjects used for validation) achieved 95.1% of genotype concordance for HLA alleles at two-digit resolution and 82.4% genotype concordance at four-digit resolution (Table 1). As reported previously, alleles with high frequencies (*f* ≥ 0.025) showed better correlations between imputed and genotyped dosages (average correlation coefficient = 0.85; Supplementary Material, Fig. S1A). These results are comparable with our previous assessments of HLA variant imputation (12,15,16), and we thus considered this approach to be suitable for downstream association analysis.

To compare the imputation performance of this new Asian HLA reference panel to our previous HLA panels (14,16), we also constructed three additional reference panels including European subjects (Supplementary Material, Table S1). These were (i) HapMap Europeans (CEU founders; *n* = 120) (14), (ii) unrelated European subjects from Type 1 Diabetes Genetics Consortium (T1DGC; *n* = 5,225) (16,17) and (iii) multiethnic panel combining the T1DGC European subjects and the pan-Asian panel described above (i and ii; *n* = 5225 + 441 = 5666).

When we used the small reference panel of HapMap CEU founders (*n* = 120), the imputation performance was limited (44.5% genotype concordance for four-digit alleles and average correlation coefficient = 0.49 for high-frequency alleles (*f* ≥ 0.025); Table 1; Supplementary Material, Figure S1B). In contrast, the large-scale reference panel from the T1DGC (*n* = 5225) yielded much better accuracy (83.5% genotype concordance for four-digit alleles and average correlation coefficient = 0.880 for high-frequency alleles), though slightly worse than the accuracy of the Asian-only reference panel (Table 1; Supplementary Material, Fig. S1C). The combined reference panel of Asians and Europeans (*n* = 5666) demonstrated comparable or better imputation accuracy than the Asian or European panel alone (87.2% genotype concordance for four-digit alleles and average

Table 1. Concordance of genotyped and imputed HLA alleles in HapMap Asian populations

Imputation reference panel	Allele	Concordance of genotyped and imputed HLA alleles in HapMap JPT+CHB ($n = 89$)						
		HLA-A	*HLA-B*	*HLA-C*	*HLA-DRB1*	*HLA-DQA1*	*HLA-DQB1*	6 HLA genes
Asian reference panel	Two-digit	0.989	0.870	**1.000**	**0.904**	0.949	**0.994**	**0.951**
($n = 441$)[a]	Four-digit	0.751	0.722	**0.932**	**0.762**	0.903	0.874	0.824
European reference panel	Two-digit	0.747	0.429	0.588	0.494	0.624	0.871	0.625
(HapMap CEU, $n = 120$)	Four-digit	0.644	0.352	0.480	0.280	0.545	0.366	0.445
European reference panel	Two-digit	0.972	0.894	0.966	0.826	0.944	0.916	0.920
(T1DGC consortium, $n = 5225$)	Four-digit	0.819	0.835	0.898	0.685	0.892	**0.880**	0.835
Asian and European reference panel	Two-digit	**0.994**	**0.898**	**1.000**	0.890	**0.978**	0.921	0.947
($n = 5666$; T1DGC for European)[a]	Four-digit	**0.864**	**0.841**	**0.932**	0.744	**0.972**	**0.880**	**0.872**

The highest concordance rates for each HLA gene are indicated in bold, separately for two- and four-digit alleles.
[a]The subjects used for validation (HapMap JPT + CHB) were excluded.

correlation coefficient = 0.91 for high-frequency alleles; Table 1; Supplementary Material, Fig. S1D). The Asian reference panel showed modest imputation performance for four-digit alleles of *HLA-A* and *HLA-B* ($<75.1\%$), whereas the combined Asian and European panel yielded improved concordance rates ($>84.1\%$). We note that improvement in imputation accuracy was not consistent for all HLA genes; the combined Asian and European panel showed slightly lower accuracy for *HLA-DRB1* alleles (76.2% genotype concordance for four-digit alleles for the Asian-only panel and 74.4% for the combined panel).

Risk of *HLA-DRB1* variants in the Asian RA samples

Having demonstrated the accuracy of our imputation protocol, we imputed HLA alleles and tested them for association in two RA GWAS and one RA Immunochip datasets of Asian ancestries (a GWAS including 466 ACPA-positive RA cases and 873 controls from China [18]; a GWAS including 799 ACPA-positive RA cases and 751 controls from South Korea [19]; an Immunochip study including 1517 ACPA-positive RA cases and 2691 controls from South Korea [20]; in total, 2782 ACPA-positive RA cases and 4315 controls). We adopted the pan-Asian imputation reference panel due to its reliable imputation accuracy on *HLA-DRB1* alleles and similar genetic backgrounds to the subjects in the Asian RA GWAS, while we note that the following association analysis results did not change substantially when we adopted the large-scaled European reference panel or the combined panel of Europeans and Asians. We incorporated top five principal components (PCs) for each cohort as covariates in the logistic regression model to correct for population stratification. After adjustment with PCs, we did not observe apparent inflation of test statistics genome wide ($\lambda_{GC} < 1.05$).

We then tested two- and four-digit classical HLA alleles, amino acid polymorphisms, and SNPs within the MHC for association, and observed the top association signal at *HLA-DRB1* (Fig. 1A). After conditioning on all classical *HLA-DRB1* alleles, no other variants were significantly associated with RA risk with a genome-wide significance threshold (conditioned $P > 5.0 \times 10^{-8}$; Fig. 1B).

The most significant association across all variants tested was observed at amino acid position 13 of HLA-DRβ1 ($P_{omnibus} = 6.9 \times 10^{-135}$) followed by position 11 of HLA-DRβ1 ($P_{omnibus} = 1.7 \times 10^{-129}$), which is in tight linkage disequilibrium (LD) with position 13. Associations for amino acid positions 70–74 (which define the SE) were considerably weaker (Fig. 2A, $P_{omnibus} > 1.6 \times 10^{-58}$). Of the amino acid residues at positions 11 and 13, His13 and Val11 showed the strongest RA risk [odds ratio (OR) = 2.03 for His13 and OR = 2.16 for Val11; Supplementary Material, Table S3]. These results are consistent with our previous results in Europeans, which demonstrated the most significant RA risk at position 11 of HLA-DRβ1, notably Val11 [12].

Applying stepwise conditional regression analysis, we observed that independent HLA-DRβ1 amino acid positions confer independent risks on RA (Fig. 2A). When conditioning on DRβ1 positions 11 and 13, amino acid position 57 showed the most significant independent evidence of association (conditional $P_{omnibus} = 2.2 \times 10^{-33}$), with amino acid positions 37, 74 and 86 demonstrating similar levels of evidence (conditional $P_{omnibus} = 1.2 \times 10^{-27}$, 1.0×10^{-30} and 1.5×10^{-22}, respectively). Conditioning on positions 11, 13 and 57 demonstrated an independent association of amino acid position 74 (conditional $P_{omnibus} = 1.1 \times 10^{-8}$). No significant associations were observed after adjusting for the effects of positions 11, 13, 57 and 74 (conditional $P_{omnibus} > 1.6 \times 10^{-6}$), suggesting that the combination of these amino acid positions explain the majority of the *HLA-DRB1* risk in Asians.

Because we had previously highlighted a role for positions 11, 13, 71 and 74 in Europeans [12], we also evaluated this specific combination. We found that these amino acid positions were also able to explain the majority of the risk, while the degree of significance after conditioning was relatively less conservative (conditional $P_{omnibus} > 2.9 \times 10^{-11}$ at amino acid position 70 and others). To find the best combination of HLA-DRβ1 amino acid positions in Asians, we tested all possible combinations of single, two and three amino acid positions (Fig. 2B; positions 11 and 13 were considered as a single position due to their strong LD and local vicinity). We found that both HLA-DRβ1 amino acid models (positions at 11, 13, 57 and 74 versus positions at 11, 13, 71 and 74) demonstrated a significantly better goodness-of-fit among all possible combinations of the tested positions (permutation $P < 0.05$, 0.001, 0.001 for single, two and three position models, respectively). Addition of the position 57 to the positions 11, 13, 71 and 74 did not demonstrate independent fitness improvement ($P = 0.36$), and addition of the position 71 to the positions 11, 13, 57 and 74 did not, either ($P = 0.52$). Genetic risk scores obtained from these two models were highly correlated ($R^2 = 0.96$). Imputation quality
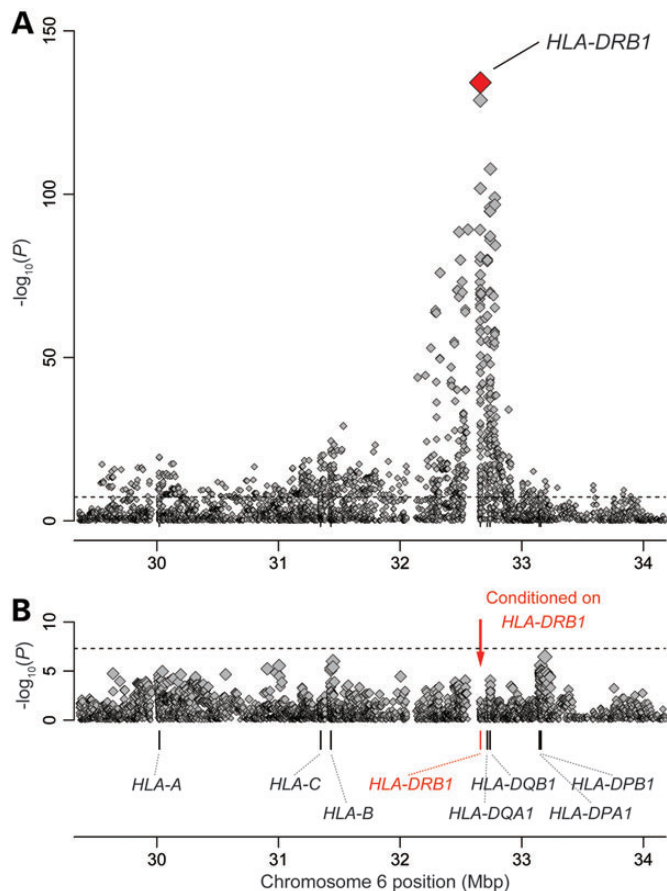
Figure 1. Association plots of the tested variants in the MHC region to ACPA-positive RA in Asians. Each diamond represents $-\log_{10}(P)$ of the variants, including the SNPs, the classical HLA alleles and the amino acid polymorphisms of the HLA genes. The dotted horizontal line represents the significance threshold of $P = 5.0 \times 10^{-8}$. The bottom panel showed the physical positions of the HLA genes on chromosome 6 (NCBI Build 36). (**A**) Nominal associations in the RA GWAS of Asians, in which HLA-DRβ1 amino acid polymorphisms showed the most significant associations. (**B**) Conditional results on *HLA-DRB1*, in which no variants showed significant associations.

scores of the residues of these amino acid positions were high (average r^2 scores by SNP2HAP = 0.96), and no apparent heterogeneity among the datasets were observed (Supplementary Material, Table S3). Thus, it would be difficult to robustly distinguish these models from each other given the relatively modest sample size of the present study. We note that all the HLA-DRβ1 amino acid residues pinpointed by our association analysis, including newly suggested position 57 (23), are located in the binding groove of HLA-DR, consistent with their functional contributions to RA pathogenesis (Fig. 2C).

HLA amino acid haplotype risks on RA are shared between Asians and Europeans

We compared RA risks of amino acid polymorphism haplotypes between Asians and Europeans. For HLA-DRβ1 amino acid polymorphisms, we selected positions 11, 13, 71 and 74, based

on the RA risk model from our previous European study (12). We first assessed the associations of the haplotypes defined by positions 11, 13, 71 and 74 of the HLA-DRβ1 amino acid polymorphisms, and observed significant correlation of effect sizes (expressed as the log OR) between Asians and Europeans ($r = 0.944$, $P = 3.8 \times 10^{-7}$; Fig. 3; Table 2). The Val11-His13-Lys71-Ala74 haplotype confers the greatest risk not only in Europeans (OR = 4.44, 95% confidence interval [95% CI]: 4.02–4.91) but also in Asians (OR = 3.63, 95% CI: 2.63–5.00, $P = 3.4 \times 10^{-15}$). When we considered the HLA-DRβ1 amino acid model based on the current Asian study (positions 11, 13, 57 and 74), we confirmed that effect sizes were significantly correlated between Asians and Europeans ($r = 0.94$, $P = 5.0 \times 10^{-7}$; Supplementary Material, Fig. S2 and Table S4).

We then compared the amino acid polymorphism risks other than *HLA-DRB1*. We selected the HLA-B position 9 and HLA-DPβ1 position 9, which are independent risk variants in Europeans (12). We observed that the effects of these variants were significantly replicated in Asians with consistent direction (OR = 4.21, 95% CI: 2.29–7.74, $P = 3.8 \times 10^{-6}$ for HLA-B Asp9 and OR = 1.26, 95% CI: 1.13–1.40, $P = 3.0 \times 10^{-5}$ for HLA-DPβ1 Phe9; conditioned on HLA-DRβ1 polymorphisms). Collectively, the combination of amino acid polymorphisms in HLA-DRβ1, HLA-DPβ1 and HLA-B explains 5.6% of the phenotypic variance of ACPA-positive RA risk in Asians, which is <12.7% previously estimated in Europeans (12).

Trans-ethnic comparisons of RA risk HLA amino acid polymorphisms

To better understand the overlap of RA risk variants in these two populations, we compared allele frequency spectra and the LD structure around the associated amino acid polymorphisms between Asians and Europeans (Fig. 4; Supplementary Material, Table S3).

Certain alleles highlighted in our analysis had very different frequencies in European and Asian populations (Supplementary Material, Table S3). For example, HLA-DRβ1 Asp11 showed higher frequency in Asians (=0.108) but lower frequency in Europeans (=0.011; $F_{ST} = 0.042$), whereas HLA-B Asp9 showed lower frequency in Asians (=0.003) but higher frequency in Europeans (=0.118; $F_{ST} = 0.058$). We note that HLA-DRβ1 Asp11 corresponds to the classical non-SE four-digit *HLA-DRB1* allele of *HLA-DRB1*09:01*. Investigators have previously noted that *HLA-DRB1*09:01* is associated with risk of seropositive RA in Asians (10,11,24). This Asian-specific risk of *HLA-DRB1*09:01* may reflect ethnically different allele frequencies of the risk amino acid residues at the same HLA-DRβ1 amino acid position (HLA-DRβ1 Asp11).

Despite these allele frequency differences between Asian and European populations, we observed that the LD structure between amino acid polymorphisms of HLA-DRβ1 positions 11 and 13 was largely consistent in both populations, with strong LD for the Val11-His13, Pro11-Arg13 and Gly11-Tyr13 haplotypes ($r^2 > 0.80$; Fig. 4C and D). Although Val11 and His13 confer the strongest RA risk in both populations, their effect was weaker in Asians (2.16 and 2.03, respectively) than in Europeans (3.78 and 3.71, respectively; Supplementary Material, Table S3).
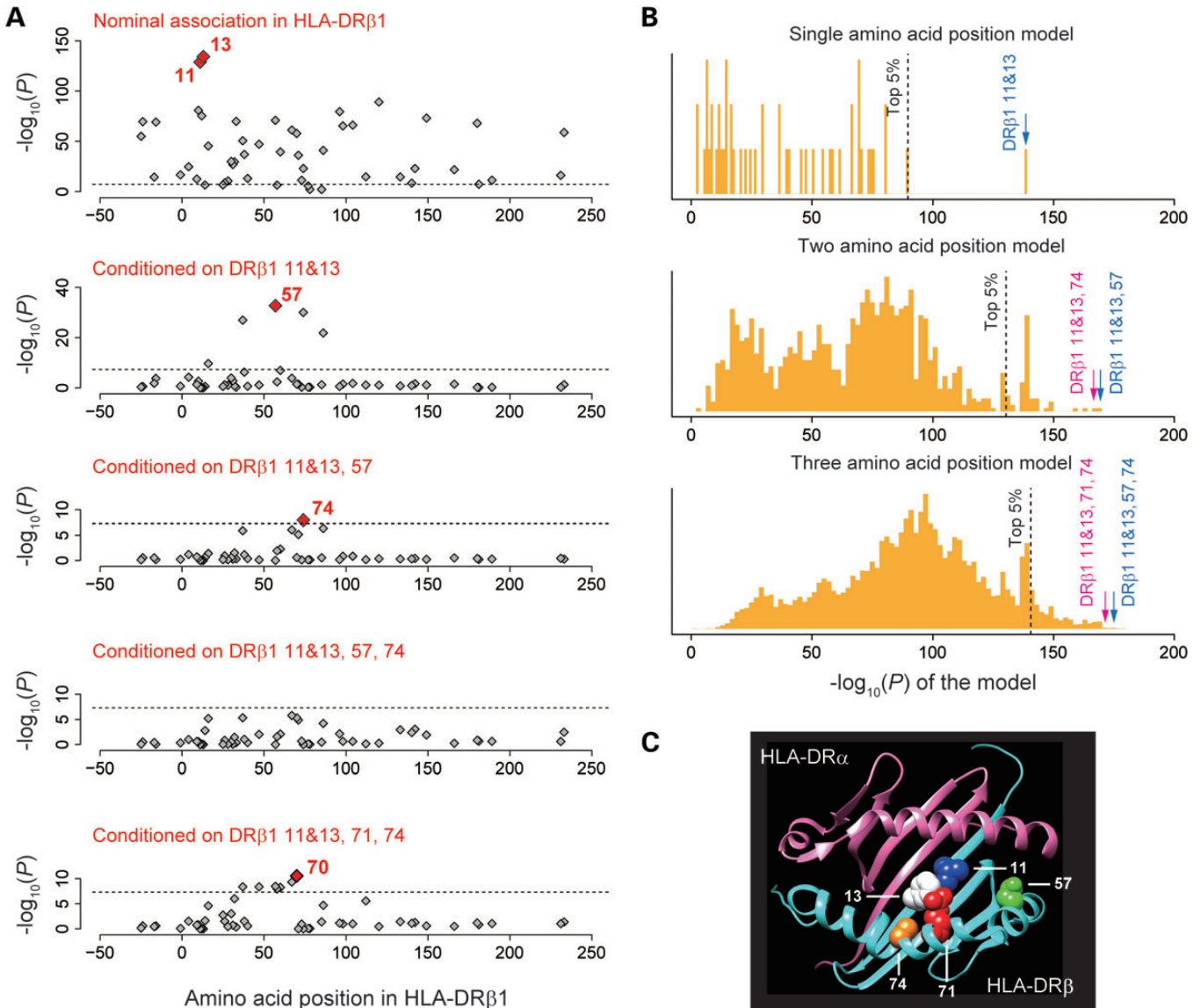
Figure 2. Association results for the amino acid polymorphisms of HLA-DRβ1. (**A**) Associations of the tested amino acid polymorphisms of HLA-DRβ1. Each diamond represents $-\log_{10}(P_{\text{omnibus}})$ of the amino acid polymorphisms. The dotted horizontal line represents the significance threshold of $P = 5.0 \times 10^{-8}$. The most significantly associated amino acid polymorphisms are labeled with their positions, while the positions of the amino acid polymorphisms in LD with them are labeled with parenthesis. Through the stepwise regression analysis for HLA-DRβ1, we found independent RA risks of positions 11, 13, 57 and 74 (top four panels), while amino acid polymorphisms reported in Europeans also showed better fitness of the model (positions 11, 13, 71 and 74; bottom panel). (**B**) Distributions of the HLA-DRβ1 amino acid position model fitness among all possible combinations of the positions. To find the best combination of HLA-DRβ1 amino acid positions to explain the RA risk in Asians, we tested the associations of all possible combination of single, two and three amino acid positions. Positions 11 and 13 were considered as a single position due to their strong LD and local vicinity. Each panel represents $-\log_{10}(P_{\text{omnibus}})$ of the model consisting of combinations of the single (top), two (middle) and three (bottom) positions of the HLA-DRβ1 amino acid polymorphisms. The dotted vertical line represents top five percentile of the $-\log_{10}(P)$ of the model. $-\log_{10}(P)$ of the models obtained from Asians (positions 11, 13, 57 and 74) and Europeans (positions 11, 13, 71 and 74) are highlighted with blue and red arrows, respectively. (**C**) 3D ribbon models for the HLA-DR protein. These structures are based on Protein Data Bank entries 3pdo (for HLA-DRβ1) (21) and prepared using UCSF Chimera version 1.7 (22). Residues at RA risk amino acid positions are highlighted as colored spheres.

DISCUSSION

Association analyses of HLA genes at amino acid sites have facilitated fine-mapping efforts in immune-related diseases (12,15). In this study, we applied this approach to ACPA-positive RA in the Asian population, using a newly constructed reference panel for Asian ancestries, and demonstrated good imputation accuracy in Asian samples. Our study validated previously identified amino acid positions in HLA-DRβ1, HLA-B and HLA-DPβ1 from the European study, suggesting that genetic risk of the MHC region on ACPA-positive RA are generally shared between continental populations.

In the published European study, the most significant associations mapped to HLA-DRβ1 amino acid positions 11 and 13, both located outside of the classical SE hypothesis (HLA-DRβ1 70–74) (12). We note that this single site explains most of the
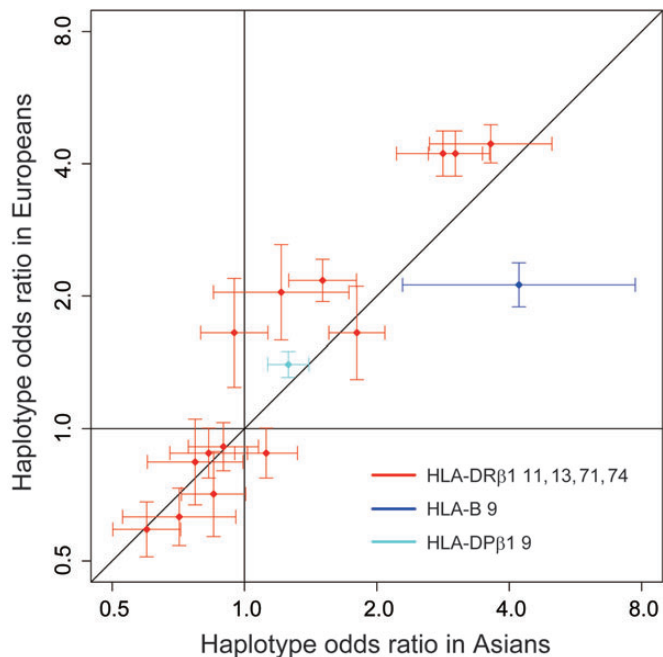
Figure 3. Comparison of haplotype ORs of RA risk HLA amino acid polymorphisms between Asians and Europeans. Odds ratios of the haplotypes consisting of the risk HLA amino acid polymorphisms and their 95% confidence intervals are plotted based on those in Asians (*x*-axis) and Europeans (*y*-axis).

variation in MHC-mediated risk for both populations, and that the residues confer similar directions and relative magnitude of risk.

We also observed that other positions in HLA-DRβ1 in European populations are generally concordant with the results presented here for Asian populations, both in terms of the specific positions identified (71 and 74 versus 57 and 74) and direction of effect of the amino acid residues at these positions. We note that amino acid position of HLA-DRβ1 57 is also located in the peptide-binding groove of HLA-DR. We cannot rule out the possibility that the observed differences could be a consequence of statistical fluctuation. Alternatively, it is possible that slight differences in the spectrum of antigens in the two populations might introduce subtle differences in which sites might play a more important role in disease susceptibility in the two populations.

In addition, we found that previously reported Asian-specific RA risk of non-SE *HLA-DRB1* allele, *HLA-DRB1*09:01*, could be explained by ethnically different allele frequencies of the residues at same HLA-DRβ1 amino acid position. These findings illustrate the value of trans-ethnic association analysis that can exploit differences in LD structure and allele frequency among populations for the fine-mapping of causal variants. We note that the (additive) effect sizes of the ACPA-positive risk HLA variants, as well as the explained heritability estimates, were smaller in Asians than in Europeans. The different magnitudes of the effect sizes might be related to population-specific gene–gene and gene–environmental interaction that have yet to be elucidated (25).

A potential limitation of our study is the relatively modest sample size of our Asian data sets, compared in particular with the studies in European populations. As a result there is the possibility that alleles which are specific to Asian populations within

HLA-DRB1 or other loci might have been missed. Such independent RA risk contributions at non-HLA genes have been frequently suggested, such as *TNF*, *MICA* and *MICB* genes (26–28). To investigate the role of such non-HLA gene variants as well as other classical genes such as HLA-DQ (29), future studies incorporating larger number of individuals from multiple ethnicities would be desirable.

This study also highlights the value of large-scale reference panels to achieve excellent imputation accuracy for HLA variants. Interestingly, the combined reference panel of Asians and Europeans yielded overall better accuracy than the respective panels we constructed for each single population.

In summary, through efficient genotype imputation of HLA variants and subsequent association analysis in two Asian populations, our study demonstrates significant sharing of HLA risk alleles with Europeans. Our study contributes to our understanding of HLA variants in the etiology of RA.

MATERIALS AND METHODS

Ethics statement

Our study was approved by the institutional review board at our institutions. All the enrolled subjects provided written informed consent for participation in the study.

Asian reference panel for imputation of HLA variants

For construction of the imputation reference panel of HLA variants for Asian ancestry, we enrolled 530 unrelated Asian subjects consisting of (i) HapMap Phase II Japanese and Han Chinese (JPT + CHB) populations (*n* = 89) (14); (ii) the Singapore Chinese population (*n* = 91) (13); and (iii) pan-Asian datasets including 111 Chinese, 119 Indian and 120 Malaysian subjects (*n* = 350). All datasets had high-density SNP genotype data and four-digit resolution of classical alleles of the class I HLA genes (*HLA-A*, *HLA-B* and *HLA-C*) and class II HLA genes (*HLA-DRB1*, *HLA-DQA1*, *HLA-DQB1*, *HLA-DPA1* and *HLA-DPB1*), except that HapMap JPT + CHB subjects did not have data for *HLA-DPA1* and *HLA-DPB1*. Part of the *HLA-DRB1*, *HLA-DQA1* and *HLA-DQB1* allele genotype data obtained from the Singapore Chinese population showed ambiguity in the resolution of four-digit alleles and provided several candidate alleles, due to similarity of the DNA sequences between these alleles and limited resolution of the genotyping methods (e.g. both *HLA-DRB1*15:01* and *HLA-DRB1*15:02* for candidate alleles) (13).

For each dataset, we encoded all variants including SNP, classical two- and four-digit HLA alleles, and amino acid polymorphisms of the HLA genes and combined them into a single reference panel (*n* = 530), using the SNP2HLA software (12,15,16). We selected the SNPs located in the region containing the entire MHC region (25–35 Mbp at chromosome 6, NCBI Build 36) which were genotyped and satisfied quality control (QC) filters in all three datasets for encoding. All variants were encoded as biallelic markers representing the presence and absence of the variants, and singletons were removed from the combined reference panel. For ambiguous four-digit alleles obtained in the Singapore Chinese dataset (13), we extracted shared amino acid sequences among the candidate four-digit

Table 2. Associations of HLA amino acid haplotypes with risk of RA in Asians

HLA-DRβ1 amino acid position				Frequency[a]		RA risk association[b]		Classical *HLA-DRB1* alleles[c]
11	13	71	74	RA case	Control	OR (95% CI)	P	
Val	His	Lys	Ala	0.022	0.009	3.63 (2.63–5.00)	3.4×10^{-15}	***04:01***
Val	His	Arg	Ala	0.228	0.092	3.02 (2.62–3.48)	8.3×10^{-53}	***04:04***, ***04:05***, ***04:10***
Val	Phe	Arg	Ala	0.038	0.017	2.83 (2.22–3.61)	6.1×10^{-17}	***10:01***
Asp	Phe	Arg	Glu	0.149	0.108	1.80 (1.56–2.09)	4.0×10^{-15}	**09:01*
Leu	Phe	Arg	Ala	0.068	0.056	1.51 (1.26–1.80)	6.2×10^{-6}	***01:01***
Pro	Arg	Arg	Ala	0.011	0.013	1.21 (0.85–1.73)	0.29	*16:02*
Ser	Gly	Arg	Ala	0.080	0.093	1.12 (0.95–1.32)	0.18	*11:05*, *12:01*, *12:02*, *12:03*
Pro	Arg	Ala	Ala	0.095	0.122	(reference)	–	*15:01*, *15:02*, *15:04*
Val	His	Arg	Glu	0.057	0.074	0.95 (0.79–1.13)	0.55	*04:03*, *04:06*
Gly	Tyr	Arg	Gln	0.048	0.075	0.90 (0.75–1.08)	0.24	*07:01*
Ser	Gly	Arg	Leu	0.066	0.092	0.85 (0.72–1.01)	0.059	*08:01*, *08:02*, *08:03*, *08:09*
Ser	Ser	Arg	Ala	0.036	0.057	0.83 (0.68–1.02)	0.070	*11:01*, *13:12*
Ser	Ser	Arg	Glu	0.021	0.032	0.77 (0.60–0.99)	0.043	*14:01*, *14:05*, *14:07*
Ser	Ser	Lys	Arg	0.013	0.026	0.71 (0.53–0.96)	0.024	*03:01*
Ser	Ser	Glu	Ala	0.049	0.099	0.60 (0.50–0.72)	1.5×10^{-8}	*13:01*, *13:02*
Ser	Gly	Arg	Glu	0.014	0.033	0.56 (0.42–0.74)	3.9×10^{-5}	*14:04*
HLA-B amino acid position 9								Classical *HLA-B* alleles
Asp				0.006	0.003	4.21 (2.29–7.74)	3.8×10^{-6}	*08*
His, Tyr				0.994	0.997	(reference)	–	*07*, *13*, *15*, *18*, *27*, *35*, *37*, *38*, *39*, *40*, *44*, *46*
								48, *49*, *50*, *51*, *52*, *54*, *55*, *56*, *57*, *58*, *59*, *67*
HLA-DPβ1 amino acid position 9								Classical *HLA-DPB1* alleles
Phe				0.862	0.826	1.26 (1.13–1.40)	3.0×10^{-5}	*02*, *04*, *05*, *16*, *28*, *31*
His, Tyr				0.138	0.174	(reference)	–	*01*, *03*, *09*, *10*, *13*, *14*, *15*, *17*, *19*, *21*, *26*

RA: rheumatoid arthritis; OR: odds ratio.

[a]Unadjusted allele frequencies of the HLA amino acid residues and the haplotypes. Haplotypes with frequency ≥0.005 in controls are indicated.

[b]Associations in HLA-B and HLA-DPβ1 were conditioned on the HLA-DRβ1 amino acid residues.

[c]Classical HLA alleles observed in the tested Asian GWAS datasets corresponding to each amino acid residue. Classical *HLA-DRB1* alleles included in Shared Epitope alleles are indicated in bold. HLA gene names and HLA alleles are conventionally written in italic.

alleles and encoded them into the panel, whereas non-shared amino acid sequences were encoded as missing genotypes (e.g. for the candidate four-digit allele set of *HLA-DRB1*15:01* and *HLA-DRB1*15:02*, amino acid sequences were identical except for the amino acid position 86 of HLA-DRβ1 and were able to be encoded by using the rest of shared amino acid sequences).

Evaluation of imputation accuracy for HLA variants

To evaluate the accuracy of the imputation, we empirically compared imputed and genotyped classical HLA alleles. We adopted HapMap Phase II JPT + CHB dataset as a gold standard to assess imputation accuracy. We pruned the SNPs by selecting ones included in the GWAS array of Affymetrix Genome-wide Human SNP Array 6.0 (Santa Clara, CA, USA), to make the genotyped SNP density similar to that in the GWAS arrays. We conducted imputation of classical HLA alleles of the HapMap subjects without including genotyped HLA allele information using the rest of the Asian reference panel [Singapore Chinese and pan-Asian datasets (*n* = 441), which was constructed separately from the original reference panel (*n* = 530)] and the SNP2HLA software (12,15,16). We then compared the concordances and correlations between imputed and genotyped allele dosages. To relatively assess imputation performances among reference panels, we also performed imputation using the two previously constructed reference panels from the European populations for HLA polymorphism imputation in the same

manner; HapMap CEU founder populations (*n* = 120) (14) and a collection from T1DGC (*n* = 5225) (16,17). Concordances of the alleles were calculated for overall two- alleles or four-digit alleles as described elsewhere (16,17). Correlations of the allele dosages were calculated for each of the two- and four-digit alleles separately by using Pearson's correlation test.

RA GWAS data in Asian populations

We used data from two GWAS and one Immunochip study from the Asian populations for 2782 cases and 4315 controls: one GWAS with the samples from China (466 cases and 873 controls) (18), one GWAS with the samples from South Korea (799 cases and 751 controls) (19) and one Immunochip study with the samples from South Korea (1517 cases and 2691 controls) (20). All cases met the 1987 American College of Rheumatology diagnostic criteria (30) and were confirmed to be ACPA positive.

Details of the GWAS and Immunochip data, including genotyping platforms, were described elsewhere (18–20). Each dataset was filtered with the stringent QC criteria as described elsewhere (18,19,31), including SNP and sample call rate cutoffs, exclusion of closely related relative and outliers in terms of ancestry, and SNP minor allele frequency (MAF) and Hardy–Weinberg equilibrium cutoffs. All subjects were confirmed to be of Asian ancestry using the results of principal component analysis conducted with HapMap Phase II populations (32). PCs estimated for QC-filtered GWAS subjects using
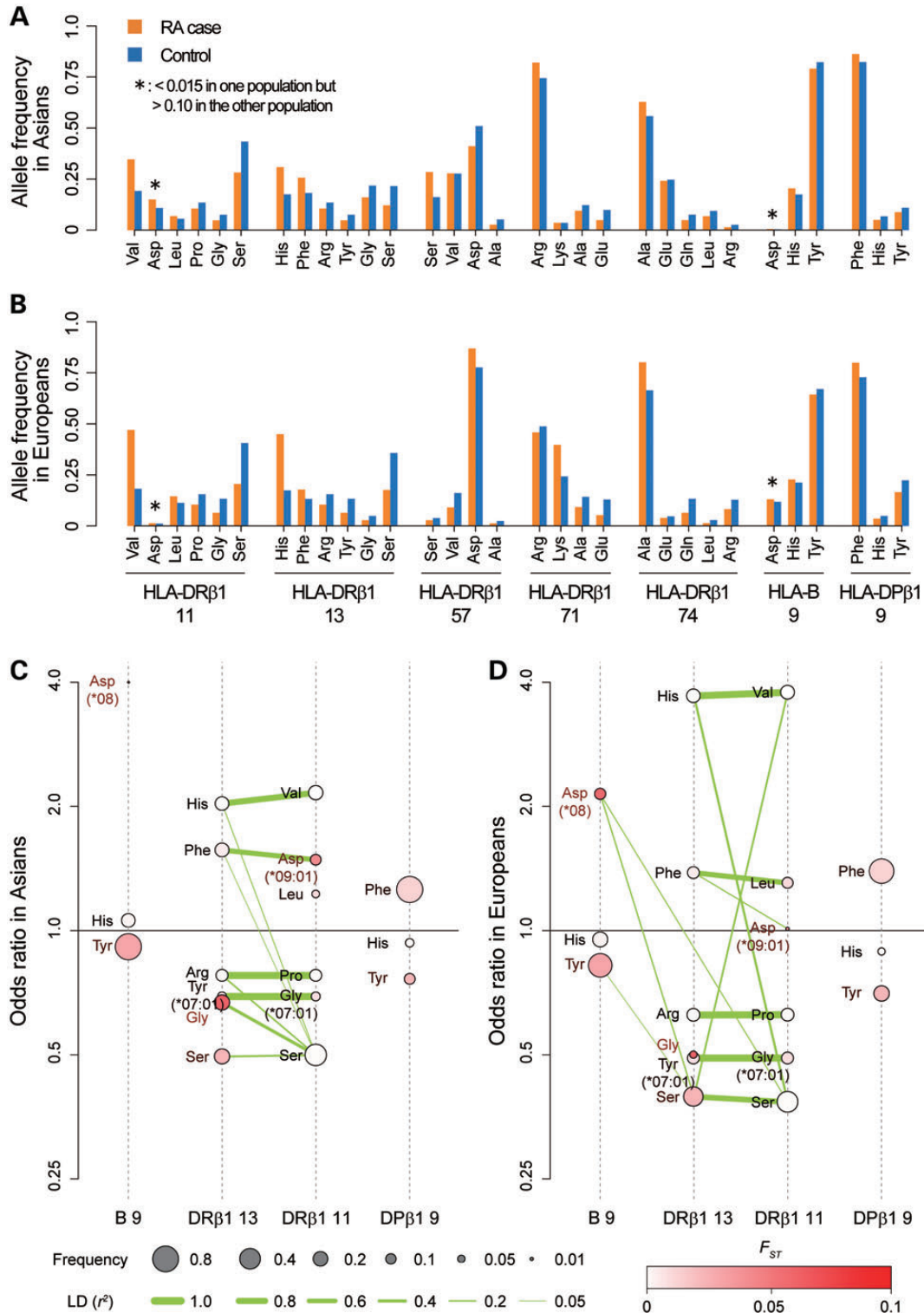
Figure 4. Trans-ethnic comparisons of allele frequencies and LD structure of RA risk HLA amino acid polymorphisms. Allele frequencies of amino acid polymorphisms with RA risks are indicated for RA cases and controls separately for Asians (**A**) and Europeans (**B**). Amino acid residues are ordered based on binominal OR obtained in Asians for each of the positions. Alleles of which frequencies are different between Asians and Europeans are highlighted with asterisks (<0.015 in one population but >0.10 in the other population). 2D visualization of LD structures between multiple alleles (or haplotypes) of HLA-B, HLA-DRβ1 and HLA-DPβ1 in Asians (**C**) and in Europeans (**D**). The dotted vertical axis indicates each of HLA amino acid polymorphisms. The points on the axis represent respective amino acid residues (or haplotypes), of which vertical positions represent their binominal OR of respective amino acid residues. The sizes of the points correspond to their frequencies as indicated in the legend. The density of the red color of the points corresponds to difference of the frequencies between Asians and Europeans (F_{ST}) as indicated in the legend. The segment connecting amino acid residues represents pairwise LD between them, and the thickness of the segment corresponds to the value of r^2 as indicated in the legend. The segments with LD of $r^2 < 0.05$ are not indicated.

whole-genome SNP data was used to correct potential population structures in the following analysis focusing on the MHC region.

Imputation of HLA variants in Asian RA GWAS data

From each GWAS, we extracted SNP genotypes located in the entire MHC region (2142 SNPs for the Chinese GWAS, 2232 SNPs for the South Korean GWAS and 5393 SNPs for the South Korean Immunochip study from 25 to 35 Mbp at chromosome 6, NCBI Build 36) to impute classical two- and four-digit HLA alleles and amino acid polymorphisms of the HLA genes along with the SNPs that were not genotyped in the GWAS. The imputation was conducted for each GWAS separately in conjunction of cases and controls together with the combined reference panel of the Asian populations ($n = 530$) by using the SNP2HLA software (12,15,16). We applied postimputation QC criteria of MAF $> 0.5\%$ for the association analysis.

Association analysis of HLA alleles and amino acid polymorphisms

We tested associations of the variants with the risk of ACPA-positive RA using logistic regression model assuming additive effects of the allele dosages in the log-odds scale and their fixed effects among the GWAS datasets. We defined HLA variants to include biallelic SNPs in the MHC region, two- and four-digit biallelic classical HLA alleles, biallelic HLA amino acid polymorphisms for respective residues, multiallelic HLA amino acid polymorphisms for respective positions. To account for potential population stratification, we included top five PCs estimated from each of GWAS datasets as covariates. We also included a dummy variable to represent GWAS datasets to account for study-specific confounding effects. For HLA variants with m alleles ($m = 2$ for biallelic variants and $m > 2$ for multiallelic variants), we included $m - 1$ alleles as independent variables in the regression model, excluding the most frequent allele as the reference. This resulted in the following logistic regression models:

$$\log(\text{odds}) = \beta_0 + \sum_{j=1}^{m-1} \beta_{1,j} x_j + \sum_{k=1}^{K} \sum_{l=1}^{L} \beta_{2,k,l} y_{k,l} + \beta_3 z + \varepsilon,$$

where β_0 is the logistic regression intercept and $\beta_{1,j}$ is the additive effects of the dosage of allele j for the variant (x_j). K and L are numbers of the cohorts and PCs enrolled in the analysis, respectively ($K = 3$ and $L = 5$). $y_{k,l}$ is the lth PC for kth cohort, and z is the indicator dummy variable for the three cohorts. $\beta_{2,k,l}$ and β_3 parameters are the effects of $y_{k,l}$ and z, respectively. An omnibus P-value of the variant ($= P_{\text{omnibus}}$) was obtained by a log-likelihood ratio test comparing the likelihood of null model against the likelihood of the fitted model. We assessed the significance of the improvement in fit by calculating the deviance ($= -2 \times$ the log likelihood), which follows a χ^2 distribution with $m - 1$ degree(s) of freedom.

For the conditional analysis, we assumed the logistic regression model additionally including the variants as covariates, which we refer 'conditional' throughout the text. For conditional analysis on the specific HLA amino acid positions, we included the multiallelic variants of the amino acid residues as covariates. For conditional analysis on the HLA gene, we included all the amino acid positions and classical HLA alleles as covariates. Amino acid positions and the HLA genes to be included as covariates were consecutively selected in a forward stepwise fashion (33).

We compared fitness of the HLA-DRβ1 amino acid models (positions at 11, 13, 57 and 74 for the model from the current Asian study and positions at 11, 13, 71 and 74 for the model from the previous European study) by a conditional analysis. Fitness of the model was evaluated by applying ANOVA test between the model including all risk HLA-DRβ1 amino acid positions (11, 13, 57, 71 and 74) and the model not including the representative position of each model (11, 13, 71 and 74 for evaluating the model from the current Asian study and 11, 13, 57 and 74 for evaluating the model from the previous European study). Calculation of genetic risk scores of the models was described elsewhere (34).

Trans-ethnic comparisons of HLA variant risks on RA

For trans-ethnic comparisons of HLA variant risks, we obtained distributions of the amino acid polymorphism frequencies and their risks on ACPA-positive RA from the previous study in the European populations (12). Allele frequency differences of the amino acid polymorphisms between Asian and Europeans were evaluated based on frequencies of the respective residues in the controls using F_{ST} (35). Correlations of HLA-DRβ1 amino acid haplotypes between Asians and Europeans were assessed by using Pearson's correlation test for logarithm of ORs. Phenotypic variance explained by the RA risk amino acid polymorphisms were estimated using liability threshold model under the assumption of disease prevalence of 0.5% (12,36). Trans-ethnic comparison of LD between the HLA variants were assessed using the phased haplotype data in the reference panels of Asians ($n = 530$) and Europeans (T1DGC consortium, $n = 5225$).

WEB RESOURCES

The URLs for data presented herein are as follows:
SNP2HLA, http://www.broadinstitute.org/mpg/snp2hla/.
International HapMap consortium, http://hapmap.ncbi.nlm.nih.gov
T1DGC consortium, https://www.t1dgc.org/home.cfm

SUPPLEMENTARY MATERIAL

Supplementary Material is available at *HMG* online.

FUNDING

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